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Comparison of the environmental performance of light mechanization and animal traction using a modular LCA approach

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ABSTRACT

Animal traction has supported humans in most field operations since the origin of agriculture. With the introduction of mechanization, humans gained access to much more work power at similar management costs and were able to significantly increase the productivity and time efficiency of field operations. This achievement completely changed food production systems for all populations able to access such technology. Nowadays, animal traction is mainly used in the developing countries, in specific contexts such as mountainous areas due to the difficulties in using tractors, and within farm tourism in the developed countries.

Although the consumption of non-renewable resources is clearly higher in crop production systems that use mechanized traction, tractor traction may involve low consumption of fuel relative to that needed for feed production for equivalent draught animals. Mechanical traction can also facilitate precision agriculture, which uses less fuel, while animals, as living systems, consume resources even when they are not working.

This study compared the environmental performance of animal traction with that of machine traction in two scenarios: (I) A forest harvesting system, using as the functional unit the logging operations needed to obtain 50 t market-ready wood and (II) a seedbed preparation system, using as the functional unit the management of 1000 m2 of prepared seedbed. Use of animal traction for these two systems was evaluated on the La Masca farm in Roccaverano, Asti, Northern Italy, while use of machine traction was evaluated using field data on two-wheel tractors performing the operations in similar production systems, converted to the specific functional unit.

Owing to the differing properties of mechanical and living systems, it was difficult to establish a reliable standard LCA model of the forestry and food production system. In particular, it proved necessary to include the whole life cycle impacts from tractors and animals. Therefore, we applied a modular LCA approach in which all mechanical implements and animals were accounted as independent modules, a complete life cycle impact assessment phase was performed and results were related to the contribution of the module in the main workflow of the scenario. The final results showed better environmental performance of animal traction both per unit weight of market-ready wood and per unit surface area of prepared seedbed.

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1 Introduction

1.1 Background of the study

Since the origin of agriculture until shortly after the end of the Second World War, animal traction supported humans in most field operations. This allowed human populations to grow faster because it significantly increased agricultural yield with a minimum increase in energetic inputs. The introduction of mechanization in agriculture and forestry completely changed this in the so-called developed countries, while animals still provide a large percentage of the traction for many developing countries (more than 50% in Africa and Asia) (Tsujimoto et al., 2005).

Since the 1980s, a number of studies have attempted to design new animal-drawn implements or improve existing models, but they have focused mainly on conditions in poorer countries (Harbans, 1985; Hedman, 1987; Singh, 1988; Lawrence and Pearson, 2002). However, animal-drawn machines may be the only option in hilly areas of developed countries, where constraints to mobility and working operations are frequent for both wheeled tractors and small cultivators. For these reasons, a French association, Prommata (*Promotion du machinisme moderne agricole à traction animale*) has developed specific implements to be used in mountainous and sloping areas (e.g. the multifunctional '*kassine*', a cart tool carrier, which allows simpler attachment of agricultural devices such as a plough to the animal).

Despite the importance of animal traction in different areas of the world, precise studies of the environmental performance of animal traction in forestry and farming systems are quite rare. Rydberg and Jansén (2002) compared horse and tractor traction using emergy analysis and found that while the total energy per unit of traction power generated was lower for mechanical systems, the main difference was in the nature of the energy used. In that case 60% of the horse inputs were renewable, compared with only 9% of inputs from the tractor. Spugnoli and Dainelli (2013) performed a Life Cycle Assessment (LCA) on the draught power of cattle in different scenarios using a very detailed model for the animal life cycle and calculating energy use and greenhouse gas (GHG) emissions. However, in the systems investigated cattle were used both for draught power and food production, creating a number of allocation problems. Engel et al. (2012), who were the first to calculate the environmental performance of draught horses for forestry operations using LCA, found that per hectare of forestry logged, a mixed animal-mechanized system had almost 45% lower GHG emissions than a fully mechanized system. They therefore concluded that as regards just GHG emissions, horses are more climate-friendly than large-scale machines, despite their lower harvesting capacity per hectare of spruce.

Within assessment methodology, LCA is one of the most widely used analytical frameworks for environmental assessment in agricultural systems (Nemecek et al., 2011) and several modifications of the basic method are currently under development. A major issue that is becoming increasingly important is the need to quantify services involved in the product life cycle that are not directly related to the consumption of resources, such as social or medical aspects. To resolve this issue, some authors (e.g. Wilting, 1996; Padovan et al., 2012) suggest including partial frameworks of

Input-Output Analysis (IOA) in the LCA calculation method. However, such a hybrid LCA/IOA requires very detailed data at the national level, which are rarely available or difficult to access. Another possibility for including impacts from the whole animal lifespan into the assessment is to perform a modular LCA covering the life cycle of the tractor/animals.

The aim of the present study was to compare the environmental performance of animal draught power with that of tractor power in the context of a high hill area in northern Italy. A modular LCA approach was adopted to compare the methods of providing traction for both forestry and soil preparation tasks. Environmental impact potentials from main ecosystem-health impact categories were considered.

1.2 Animal traction today, why it is important?

Despite the advantages of animal draught power under some local conditions, there is an ongoing debate about its environmental benefits in comparison with tractors. Supporters of mechanical traction point out that tractor work involves lower consumption of fuel that that needed to produce the feed consumed by animals to carry out the same amount of work. Furthermore, the impacts of tractors have to be related to the larger amount of traction they provide compared with animals, due to differences in their power output.

In developed countries, use of animal power, such as draught horses, is generally confined to specific contexts, such as protected areas (McCabe and Tiner, 1992), where it provides a low impact alternative to conventional machinery (Bahls, 1991). However, there are several other reasons for resorting to animal power in highly developed countries. At present, 200,000 farms in the USA use draught horses, whereas around 100 farms do so in Germany (Moscardo, 2010). However, these numbers may increase in future considering the energetic and environmental problems in a scenario where the availability of fossil fuels has peaked (Hopkins, 2008). In the short-term, the use of draught horses (or mules or donkeys) may be particularly interesting in alpine areas, where mechanization is environmentally and economically unsustainable. In these marginal contexts, equines fit perfectly with the idea of farm multifunctionality, which is the only opportunity to keep people living and working in marginal areas of otherwise highly developed countries.

Moreover, the use of heavy machinery in forestry or agricultural operations and harvesting can result in severe degradation of soil quality and consequent loss of productivity (Curran et al., 2005). This problem is of particular relevance on mountains or other steep slopes, where forest soils are poorly developed and the thickness of soil mantle is naturally low. In these areas, disturbances have been identified in the creation of a capillary logging trails network, which is necessary for machine access to forest plots for the extraction and transport of the timber. In addition, the harvesting equipment has a direct impact on the soil in the plots. In these fragile environments, loss of disturbed topsoil results in a dramatic decrease in soil fertility because of the poor physical condition of the deeper soil horizons and the loss of organic matter and nutrients partly linked to increased erosion (Hartanto et al., 2003). The most commonly recognized degradation effects are soil compaction and erosion, mainly linked to disturbances in soil physical properties, such as soil structure, bulk density, porosity and water infiltration. In addition, soil chemical properties and nutrient cycling in the soil-plant system can be directly and indirectly affected by field operations, raising major concerns about the maintenance of soil productivity and environmental quality (Gartzia-Bengoetxea et al., 2009).

In addition to soil disturbance in sloping alpine valleys, another factor preventing widespread agricultural mechanization is that farms are often too small for mechanized operations and that their cost-effectiveness is heavily affected by fixed costs (Väätäinen et al., 2006). Even light machinery may be a problem on rough, sloping and inaccessible terrain (De Lasaux et al., 2009). Moreover, the complete replacement of draught horse power with machinery would lead to loss of heritage as regards use of animal power, which dates back to the Bronze Age, when the first horses were domesticated and trained to perform work for humans.

Besides being employed in forestry operations, horses and donkeys in alpine valleys can help maintain mountain pastures to a higher degree than ruminants because of their frugality and sturdiness (Hippoliti and Piegai, 2000). In fact, equines are able to browse even low-quality plants and can thus improve the floristic quality of pastures by grazing. They can also graze the understorey layer in forests, where the presence of vegetation increases the wild fire hazard.

2 Methods

2.1. The need for an extended approach

Two-wheel, single-axle tractors (walking tractors) are mechanical systems, the environmental impacts of which are linearly related to the power they are able to generate. They are usually easily modelled in LCA in terms of impacts per working hour (or impact per ha in food production systems) (Nemecek et al., 2011). In contrast, animals are biological systems for which the efficiency in power generation can vary considerably for various reasons related to the life of the animal (e.g. species, age, health and ability to work). Modelling animal systems in LCA is further complicated by the fact that environmental impacts during the animal's life are not directly related to the generation of working power, but to its whole life. Engel et al. (2012) and Spugnoli and Dainelli (2013) solved this problem by considering impacts from the whole life cycle of the animals, including pregnancy, growth and maintenance, within the system boundaries of their case studies.

This methodology is useful, but suffers from two main disadvantages: lack of data, as most farmers do not have data about animals before purchase; and allocation of co-products, since when animals are used for power generation and food (such as meat or milk), it is very difficult to allocate impacts to different outputs.

A first attempt to solve these problems involved including partial frameworks of IOA in the LCA calculation method (Cerutti et al., 2012), as suggested by several authors (e.g. Wilting 1996; Hendrikson et al., 1997; Kok et al., 2003; Hertwich, 2011; Padovan et al., 2012). Using this approach, Cerutti et al. (2012) were able to account for the environmental impacts of equipment and services per € by applying an environmental extended application of the Italian Input-Output matrix (ISTAT, 2011) with NAMEA (National Accounts Matrix including Environmental Accounts) coefficients. However, due to the low level of detail in available national statistics, the impacts from machinery use could only be assessed using a broad category (in particular NAMEA sector 29: *Manufacturing of* *machinery and mechanical apparatus, including installation and repair*), which severely overestimated the impacts for the farm machinery. The same effect was observed for all services for which proxies from the economic sector were used (Cerutti et al., 2012).

Therefore in the present study we decided to move a step forward and consider the environmental impacts of machinery and equines using a modular LCA approach (Jungbluth et al., 2000; Rebitzer, 2005; Buxmann et al., 2009). This method incudes the same steps as an LCA according to the guidance given in ISO 14044, but instead of performing a single assessment of a broad system, key processes are extrapolated and managed as stand-alone sub-systems. Furthermore, a proper life cycle impact (LCI) assessment (i.e. with classification and characterization) is performed at the sub-system level according to the reference flow that links the sub-system with the rest of the production system. For example, Jungbluth et al. (2000) studied the environmental profile of the meat and vegetable consumption pattern of Swiss families through a modular approach by dividing the inventory into five modules according to product characteristics (such as agricultural practices, processing industries and distribution systems). The results of the five separate modules were then aggregated to assess the total environmental burden of a purchased product. It is important to note that inventories and impacts of each module were calculated for the functional unit of one kilogram of purchased product.

According to ISO 14044, the modular approach is allowed providing that the resulting data are not different from those obtained in a standard LCA application (Rebitzer, 2005). We applied the modular approach in order to move beyond the standard modelling of a production system in order to address the problem of a precise impact evaluation of using living systems such as animals for draught power. In particular we considered each mechanical implement and animal as a separate sub-system, with specific system boundaries including the whole life cycle and using working hours as reference flow of the module (Figure 1).

For each module, a standard LCA was performed in accordance with the guidelines and requirements of the ISO 14040 standard series and with the cradle-to-grave approach as the basis for the LCI. As all modules have to be coherent with the broad system model, all the inventories were characterized by the same impact assessment method and the same impact categories. In particular, based on the emissions estimated in the LCI analysis, the environmental impacts were calculated in the impact categories of the EDIP 1997 method (Wenzel et al., 1997). Based on the results of previous studies (e.g. Nemecek et al., 2011; Valente et al., 2011), impact categories that quantify environmental impacts on ecosystems rather than on resource consumption or human toxicity were used, with particular attention to global warming, eutrophication and acidification potential. Furthermore, in order to compare the total environmental impacts of the different scenarios against each other, weighting was performed in accordance with EDIP (1997). In this method, political targets are used to scale the importance of the different impact categories against each other. The units in which the results are expressed are person equivalents according to the target given for the future (PET).

The procedure described by Buxmann et al. (2009) was then applied. In detail, once the environmental impact potential of each independent LCA module was calculated, each module was connected to the main workflow of the system model through the number of working hours (or fractions) needed for each operation in the modelled workflow, in order to aggregate the category results of the LCA modules (Buxmann et al., 2009). See sections 2.3 and 2.4 for details of the case study systems.

One of the advantages of this approach is that it included different levels of extension from the main system boundaries and the system boundaries of the independent modules. Thus the full life cycle of animals and machines was accounted for, avoiding the problem of misestimating impacts when considering just their use phase.

2.2 Description of the system

The field work was carried out at La Masca farm in Roccaverano, on the sloping hills of the South Piedmont Region of Northern Italy, where farms and forestry were gradually abandoned during the 1960s and 1970s and where young farmers are now coming back to produce niche products, such as Robiola di Roccaverano cheese and Tonda gentile delle Langhe hazelnuts. On the La Masca farm one donkey and one mule are used to perform agricultural and forestry tasks.

As assessment of the environmental performance of animal traction in different field operations was the main objective of the study, two cases were investigated. The first examined use of the mule for logging operations in a forestry system and the second use of the donkey for tillage operations in a crop production system. Data on all operations carried out by the equines on the La Masca farm were compared with field data on the same operation carried out by walking tractors in a similar production system and then related to the specific functional unit.

Inventory data on most of the processes used within the two case studies were taken from the reference GaBi 4.0 database. However, inventory data for some processes were missing or not valid for the study, in which cases ad hoc analyses were performed.

In particular, in the animal traction LCA module, it was necessary to quantify the impacts from forage production and management as one of the main environmental burdens of the animals (Rydberg and Jansen, 2002; Spugnoli and Dainelli, 2013). In order to have scenarios corresponding to reality, the exact forage production and supply chain for the La Masca donkey and mule were considered. The equines mainly graze the farm's meadows, helping to keep the paths clean, and in addition 6000 kg of hay are purchased from a neighbour. In evaluating the environmental impact of this hay production, data on the exact machines used by the neighbour were included. Furthermore, in this module all aspects related to the life span of animals were included (Figure 1B). Based on previous studies (Engel et al., 2012), health care was taken into account by simply considering the impacts from the distance travelled by a veterinarian. In detail, two visits per year were assumed, once to undertake the necessary vaccinations against common diseases (such as rabies and tetanus) and once for a normal visit or an emergency, with a travel distance of 45 km per visit. Animal equipment was accounted for according to average emissions per kg leather using literature values (Notarnicola et al., 2011) and stables were accounted for in terms of electricity consumption.

For the tractor and mechanical implement LCA modules, we applied the approach suggested by Lee et al. (2000). All stages in the life cycle of tractors from material acquisition to disposal were accounted for (Figure 1A). Data for most stages were taken directly from technical reports and factsheets supplied by manufacturers of the actual implement. Data on disposal were taken from national statistics (ISPRA, 2012).

All information necessary for setting up the scenarios was acquired through interviews with animal owners (e.g. amount of hay fed annually to donkeys), field measurements (e.g. time needed for preparing the animal for work) and technical reports from manufacturers (e.g. amount of fuel used by a chainsaw).

2.3 Case A: Forest harvesting

In the forestry system (case study A), the environmental performance of mules and walking tractors in the forestry operations of collecting and transporting wood to the farm warehouse was evaluated. Three operational stages were considered (Figure 2): (I) felling (individual cutting of trees), limbing (removing branches) and bucking (cutting into logs); (II) yarding (collection of logs); and (III) transport from the forest to the farm. In the animal traction scenario, stage I was performed using a billhook and chainsaw (2.6 kW) and stages II and III by mule. The functional unit was set at 100 kg wood at the warehouse in both scenarios and the forest was assumed to be located around 1 km from the farm (Table 1).

To allow comparison with animal traction, the mechanical traction scenario assumed average forestry production practices in the region, i.e. stage I by chainsaw, stage II by a winch and stage III by a haul, all connected to a walking tractor. Machines and equipment suitable for harvesting 50 t wood per year were chosen (Table 2): a 3.4 kW chainsaw (the power required for winching), a winch (minimum 2.8 kW required), a 10 kW walking tractor and a haul for transport.

2.4 Case B: Seedbed preparation

In the crop production system (case study B), the environmental performance of donkey and walking tractor traction in tillage operations was evaluated. Three operational stages were considered (Figure 3): (I) ploughing, (II) application of fertilizer and (III) seedbed preparation, which involves harrowing and opening seed furrows. The functional unit was set at 1000 m^2 of prepared seedbed in both scenarios.

In the animal traction scenario, all operations were performed with agricultural implements connected to the '*kassine*' (Table 3) and the environmental impacts from fertilizer production were avoided because manure from the donkey was assumed to be applied as fertilizer.

In the mechanical traction scenario used for comparison, average farm practices in the region were assumed and the main draught machine was the walking tractor, with specific equipment attached (Table 4).

3 Results

3.1 Impacts of animal working hours and mechanical tools

The environmental impact potential per working hour of animals was: Acidification potential 3.41E-04 kg SO_2eq; global warming potential (GWP 100 years) 8.42E-02 kg CO_2eq; nutrient enrichment potential 5.73E-04 kg NO_3^-eq; ozone depletion potential 1.03E-10 kg R11-eq; photochemical oxidant potential (high NOx) 4.03E-04 kg ethene-eq; and photochemical oxidant potential (low NOx) 3.31E-04 kg ethene-eq. As manure was considered an input to another part of the system (soil fertilization), it was not included in calculation of the environmental impact per working hour. Therefore GWP was the most influential impact category, representing more than 40% of the weighted impact potential. The main components of the system generating GHG emissions per working hour (Figure 4) were associated with feeding (59.6%), equipment management (21.1%), keeping the animal (9.9%) and veterinary attendance (9.4%). Also for mechanical tools, GWP was the most influential impact category, representing almost 45% of the weighted impact potential. For mechanical tools, GHG emissions are mainly generated in their use phases. In particular for the chainsaw, winch and walking tractor, an average of 68.5% of GHG emissions are related to fuel consumption, 14.6% to lubricating oil production, 10.8% to fuel production, 5.9% to the rest of the life cycle phases, including production, disposal and management

3.2 Case A: Forest harvesting

In terms of normalized impact potential (Figure 5), the animal traction scenario showed better performance in all impact categories, with an average 75% reduction in the relative impact potential of the mechanized traction system.

In the overall environmental evaluation, achieved considering the weighted impact potential of the two scenarios (Figure 6), the animal traction scenario (1.12E-04 PET) performed better than the mechanized scenario (4.37E-04 PET).

3.3 2 Case B: Soil preparation for crops

In case B, the impacts of the animal traction scenario resulted almost exclusively from the inputs necessary during the lifetime of the animal, whereas in case A part of the impacts resulted from the use of the chainsaw in the animal traction system. As a result, the normalized impact potential of the animal traction scenario was much more favourable than mechanized traction in case B (Figure 7) as regards acidification potential, GWP and nutrient enrichment potential, while photochemical oxidant potential was very similar in both scenarios. Better overall environmental performance in case study B, evaluated considering the weighted impact potentials of the two scenarios (Figure 8), was again achieved by the animal traction scenario (1.06E-03PET) compared with the mechanized traction scenario (3.44E-02 PET).

4 Discussion

This study showed that animal traction had better environmental performance, both per unit weight of market-ready wood and per unit area of prepared seedbed, than mechanical traction. In terms of weighted impact potential, the reduction achieved using animal instead of mechanical traction was 74.4% in case A and 96.9% in case B.

This finding is generally consistent with those of previous studies comparing different indicators such as non-renewable energy (Rydberg and Jansen, 2002), horse draught power (Engel et al., 2012) and cattle draught power (Spugnoli and Danielli, 2013).

In the GWP category alone, animal traction reduced the environmental impact by 0.93 kg CO_2eq/100 kg wood (about 74%) in forest harvesting and 50.45 kg CO_2eq/1000 m^2 prepared seedbed (about 94%) in soil tillage. Considering the eco-efficiency of each scenario in terms of the quantity of goods produced per unit of emissions (Bjørn and Hauschild, 2012), the performance differed even more. In case A, emissions of 1 kg CO_2eq using mechanical traction produced 79.64 kg market-ready wood and using animal traction 311.30 kg market-ready wood. In case B, emissions of 1 kg CO_2eq using mechanical traction allows for preparation of 18.69 m^2 of seedbed while animal traction allows for preparation of 330.63 m^2 of seedbed.

Besides GHG emissions, use of animals also increased the environmental performance of soil preparation in the nutrient enrichment impact category (Figure 7). Donkey manure is one of the best organic fertilizers, with slow release of nutrients and good supply of organic matter to the soil (Bianchi et al., 2001). Furthermore, according to the literature of LCA in farming systems (Nemecek et al., 2011), as manure is a by-product of the animal sub-system, it can be included as a fertilizer the animal traction scenario in case B without having to include emissions due to its production.

It could also be interesting to consider how the results would be affected if the fuel consuming tools were running on biofuels instead of fossil fuels. For this scenario, field data was not available but some observations can be made using reference values from literature. First of all, it has to be considered that a complete replacement of fuel in all mechanical tools is not possible, because biofuels for chainsaws are discouraged in order to not damage the carburettor (Nati and Pasini, 2008). For chainsaws it is possible to use alternative fuels, such as alkylate, which are not biobased, but life cycle emission inventories for such products are not available yet. For the waking tractor it is possible to replace the fuels with biofuels. In order to give an impression of the effect on the results, emission factors for biodiesel from the literature can be used to calculate a theoretical emission reduction. Considering an GHG emission reduction of 48.8% by biodiesel compared to standard diesel (European Commission, 2010) an overall GWP reduction is estimated to be 26.4% for case A and 16.6% for case B. Furthermore, Roiz and Paquot (2013) highlight that a hot spot for GHG emission reduction in the life cycle of the chainsaw is the lubricating oil. They calculated a reduction of 83% in GWP by replacing oil of fossil origin to biofuels. Applying the product described by Roiz and Paquot (2013) in case A (the only one using the chainsaw) the reduction in GWP of the whole scenario would be 0.3%.

In total, considering a theoretical complete substitution to biobased fuels and oils, the mechanical scenario of case A would show a GWP reduction of about 26% compared to 74% obtained using animal traction, and the mechanical scenario of case B would show a GWP reduction of about 17% compared to 97% obtained using animal traction. Consequently, GWP reduction achieved by the use of animal traction can be significantly higher when substituting fossil fuel based machinery as opposed to biofuel based machines.

Use of animals for agricultural work can thus be significant for a number of reasons. There are ecological advantages related to use of renewable energy and thus a major reduction in GHG emissions. In addition, the animals provide ecological advantages in terms of grazing services and fertilizer. There is a positive social impact in terms of improvement of the life quality (i.e. animal traction can reduce pollution and noise compared with conventional agricultural machines). There are also economic advantages, as use of draught animals can create employment in remote mountainous and abandoned areas and can also help maintain local traditional crafts (harness and working machine manufacture, farriery work and other).

Application of the modular LCA approach in the present study allowed all the main processes involved in the lifetime of animals and machines to be accounted for. However, more accurate estimates of the lifespan of animals and mechanical tools are necessary to complement the dataset for more accurate results.

5 Conclusions

The use of draught equines in agricultural and forestry tasks must be evaluated in relation to the geographical context and striking a balance between economic and environmental outputs. In recent years there has been a slow but significant return to the use of donkeys, horses and mules in agricultural operations, especially in previously abandoned hilly areas which pose a risk of erosion and where mechanization is not suitable due to lack of road access.

This study showed that use of equines for agricultural work can have significant environmental advantages, particularly in terms of renewable energy use and lower GHG emissions, compared with mechanical traction. There are also ecological benefits, e.g. from animal grazing, and quality of life benefits, e.g. reduced chemical and noise pollution compared with conventional agricultural machines. Furthermore, draught animals can create employment in mountainous and abandoned areas and help maintain local traditional crafts.

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References

Bahls J., 1991. Horsepower logging. Am For, 9, 49-59.

Bianchi P.G., Castelli P.G., Centolani G., 2001. Manuale di agricoltura. 2° edizione. HOEPLI Editore – Milano.

Bjørn A., Hauschild M.Z., 2012. Absolute versus Relative Environmental Sustainability. What can the Cradle-to-Cradle and Eco-efficiency Concepts Learn from Each Other? Journal of Industrial Ecology, in press, DOI:10.1111/j.1530-9290.2012.00520.x

Buxmann K., Kistler P., Rebitzer G., 2009. Independent information modules—a powerful approach for life cycle management. International Journal of Life Cycle Assessment, 14(S1):S92–S100

Cerutti A.K., Tosco J., Bruun S., Calvo A. 2012. Comparison of environmental performance of tractor and animal traction using a hybrid-LCA. Proceeding of the SETAC 18th LCA Case Study Symposium, 26-28 November 2012, Copenhagen, pag 113

Curran, M.P., Heninger, R.L. Maynard, D.G., Powers, R.F. 2005. Harvesting effects on soils, tree growth, and long-term productivity. In: Productivity of Western Forests: A Forest Products Focus, Chapter One. United States Department of Agriculture, Forest Service. Pacific Northwest Research Station. General Technical Report PNW-GTR-642. August 2005.

De Lasaux, M., Hartsough, B., Spinelli, R., Magagnotti, N. 2009. Small parcel fuel reduction with a low-investment, high-mobility operation. West J Appl For, 24, 205-213.

Engel A. M., Wegener J., Lange M., 2012. Greenhouse gas emission of two mechanized wood harvesting methods in comparison with the use of draft horses for logging. European Journal of Forest Research. 131:1139–1149.

European Commission, 2010. How to develop a Sustainable Energy Action Plan (SEAP) – Guidebook. Luxembourg: Publications Office of the European UnionGartzia-Bengoetxea, N., Gonzalez-Arias, A., Kandeler, E., Martinez de Arano, I. 2009. Potential indicators of soil quality in temperate forest ecosystems: a case study in the Basque Country. Ann. For. Sci. 66, 303.

Hartanto, H., Prabhu, R., Widayat, A.S.E., Asdak, C. 2003. Factors affecting runoff and soil erosion: plot-level soil loss monitoring for assessing sustainability of forest management. Forest Ecology and Management, 180, 361–374.

Harbans L. 1985. Animal-drawn wheeled tool carrier: an appropriate mechanization for improved farming systems. Ama, Agricultural Mechanization In Asia, Africa And Latin America, 16, 1, 38-44.

Hedman L. 1987. Tools and equipment for horse logging. Small Scale Forestry. 1: 422, 10-17.

Hendrickson, C. T., A. Horvath, S. Joshi, M. Klausner, L. B. Lave, and F. C. McMichael 1997. Comparing two life-cycle assessment approaches: A process model versus economic input-output-based assessment. Proceedings of the I 997 IEEE International Symposium on Electronics and the Environment, 176–181.

Hertwich, E.G. 2011. “The life cycle environmental impacts of consumption.” Economic Systems Research, 23(1):27-47.

Hippoliti G., Piegai F. 2000. Tecniche e sistemi di lavoro per la raccolta del legno. Ed. Compagnia delle Foreste, Arezzo.

Hopkins, R. 2008. The Transition Handbook: from oil dependency to local resilience. Green Books.

ISTAT, 2011. Tavole delle risorse e degli impieghi. Italian National Institute of Statistics. Rome, IT

ISPRA, 2012. Rapporto Rifiuti Speciali – Report n. 174/2012. Istituto Superiore per la Protezione e la Ricerca Ambientale, Rome, IT

Jungbluth N., Tietje O., Scholz R.W., 2000. Food Purchases: Impacts from the Consumers' Point of View Investigated with a Modular LCA. International Journal of Life Cycle Assessment, 5(3)134-142

Kok R., Falkena H.J., Benders R.M.J., Moll H.C., Noorman K.J., 2003. Household metabolism in European countries and cities. IVEM Report

Lawrence P.R., Pearson R.A., 2002. Use of draught animal power on small mixed farms in Asia. Agricutual Systems 71:99–110.

Lee J., Cho H., Choi B., Sung J., Lee S., Shin M., 2000. Life Cycle Assessment of Tractors. International Journal of Life Cycle Assessment, 5:205-208

McCabe, P., Tiner, E. 1992. Mule logging: a dying art? Treasures Forests, 405 Spring Issue, 14-15.

Moscardo, A. 2010. Il cavallo da lavoro non va in pensione. MAD (Macchine Agricole Domani), 3, 47-49.

Nemecek T, Huguenin-Elie O, Dubois D, Gaillard G, Schaller B, Chervet A, 2011. Life cycle assessment of Swiss farming systems: II. Extensive and intensive production. Agric Syst 104:233–245.

Nati, C., Pasini, A. 2008. Ricerca su carburanti e lubrificanti "ecologici" per motosega. Alberi e Territorio, 1, 47-51.

Notarnicola B., Puig R., Raggi A., Fullana P., Tassielli G., De Camillis C., Mongelli I., Rius A., 2011. Life Cycle Assessment of Italian and Spanish Bovine Leather Production Systems. Afinidad, 68:167-180..

Padovan D., Martini F., Cerutti A.K., 2012. Methodologies and early results in the application of the Energy Analysis Program to the Italian context. Energy Issues and Social Sciences, Theories and Applications, Eds. Alfredo Agustoni and Mara Maretti, McGraw-Hill publication, Chapter 6:61-69

Rebitzer G., 2005. Enhancing the application efficiency of life cycle assessment for industrial uses. PhD Thesis, Swiss Federal Institute of Technology, Lausanne (EPFL)

Roiz J., Paquot M., 2013. Life cycle assessment of a biobased chainsaw oil made on the farm in Wallonia. International Journal of Life Cycle Assessment, 18:1485-1501

Rydberg T., Jansén J., 2002. Comparison of horse and tractor traction using emergy analysis. Ecol Eng 19:13–28. doi:10.1016/S0925-8574(02)00015-0

Singh, S.N. 1988. Agriculture and Agricultural Mechanization in India. Journal of the Institution of Engineers (India). Agricultural Engineering Division, 68, 57-61.

Spugnoli P., Dainelli R., 2013. Environmental comparison of draught animal and tractor power. Sustainability Science, 8:61-72

Tsujimoto, T., Sakurai, H., Hashiguchi, K., Inoue, E. 2005. Study on the Development of Agricultural Machines for Small-Scale Farmers. Part I. *Agricultural Mechanization in Asia, Africa, and Latin America*. 36, (1), 79-84.

Väätäinen, K., Asikainen, A., Sikanen, L., Ala-Fossi, A. 2006. The cost effect of forest machine relocations on logging costs in Finland. Forestal Studies, 45, 450, 135-141.

Valente C., Spinelli R., Gunnar Hillring B., 2011. LCA of environmental and socio-economic impacts related to wood energy production in alpine conditions: Valle di Fiemme (Italy). Journal of Cleaner Production, 19:1931–1938

Wenzel, H., Hauschild, M. & Alting, L. (1997) Environmental Assessment of Products, Vol.1: Methodology, Tools and Case Studies in Product Development. Institute of Product Development, Kluwer Academic Publishers, Hingham, MA. USA.

Wilting, H.C. 1996. An energy perspective on economic activities. PhD. Thesis, Centre for Energy and Environmental Studies: University of Groningen.

Comparison of the environmental performance of mechanized and animal traction using a modular LCA approach

FIGURES

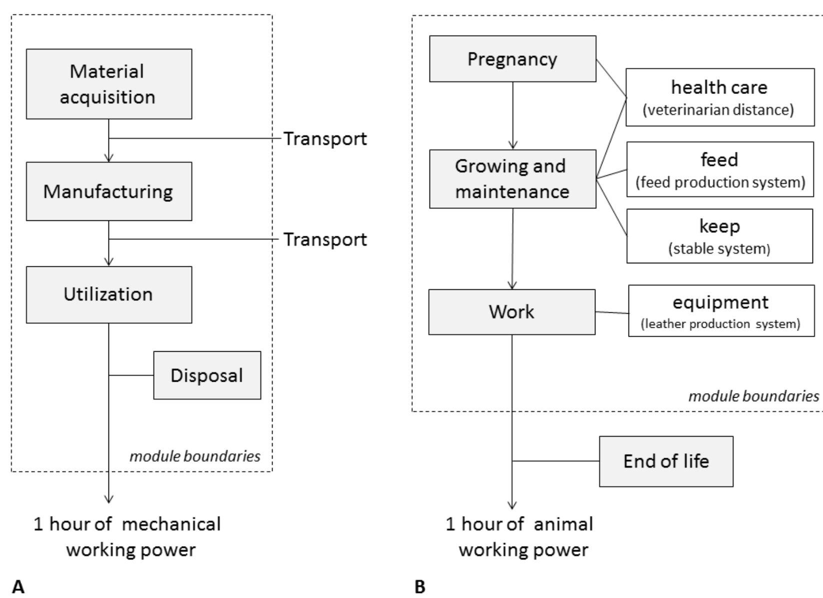

Figure 1. Graphical representation of the system boundaries considered in the modules for: (a) LCA of tractors and mechanical tools; (b) LCA of animal life-span.

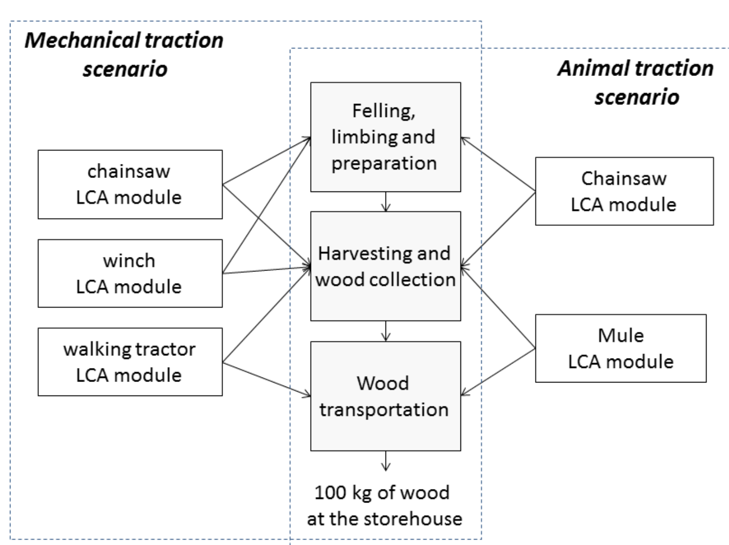

Figure 2. System boundaries in the wood production case study

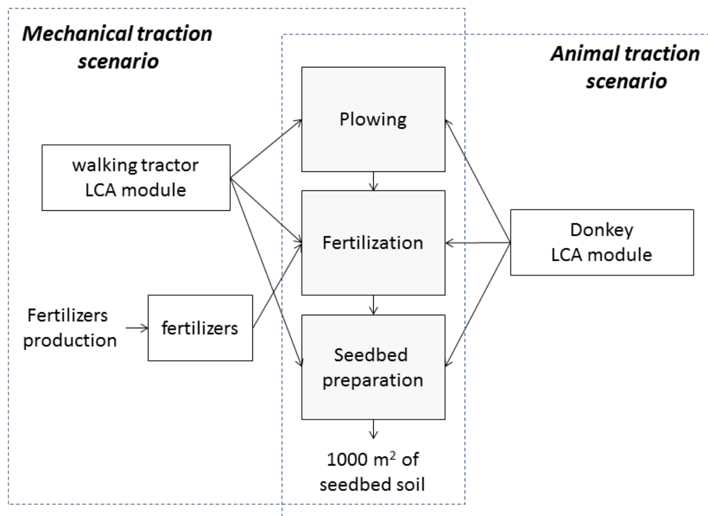

Figure 3. System boundaries in the agricultural case study

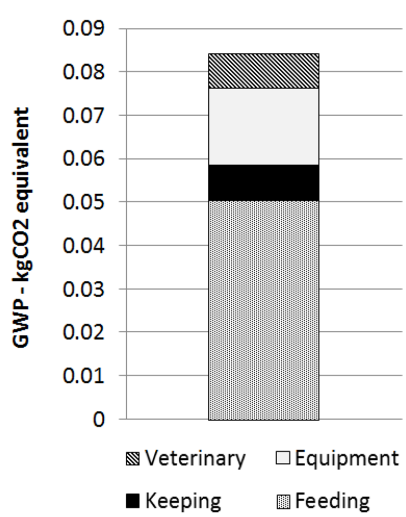

Figure 4. Breakdown of components of the Global Warming Potential (CO_2-equivalents) of 1 working hour (average) made by donkey and mule.

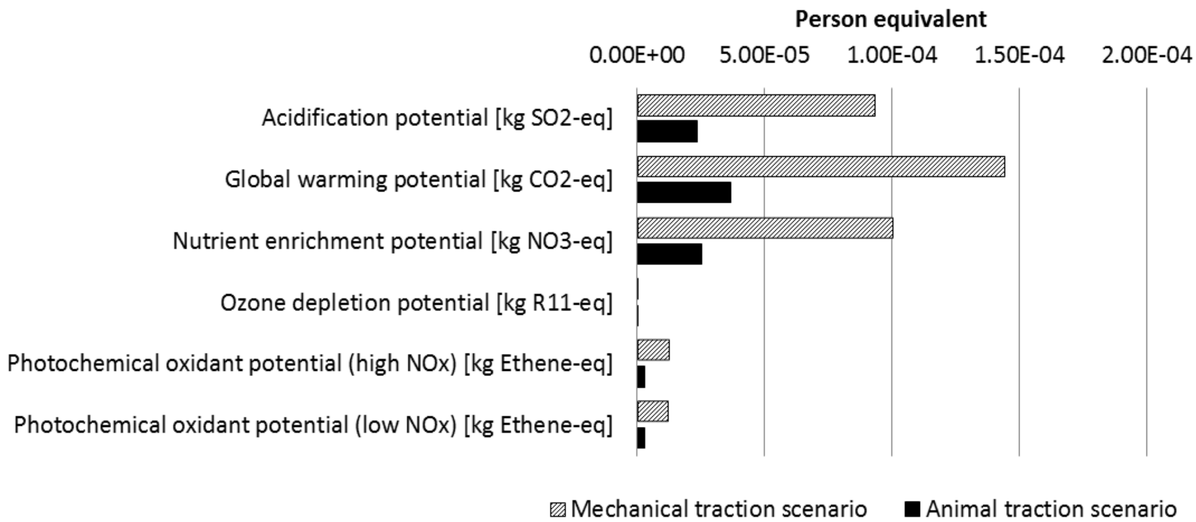

Figure 5. Case A: forestry task, normalized impact potentials

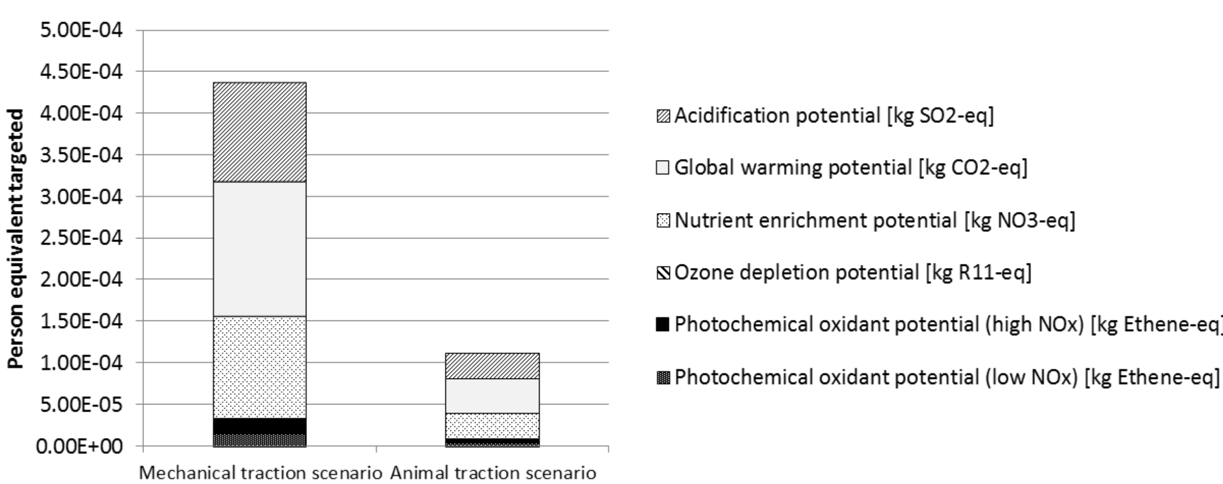

Figure 6. Case A: forestry task, weighted impact potentials

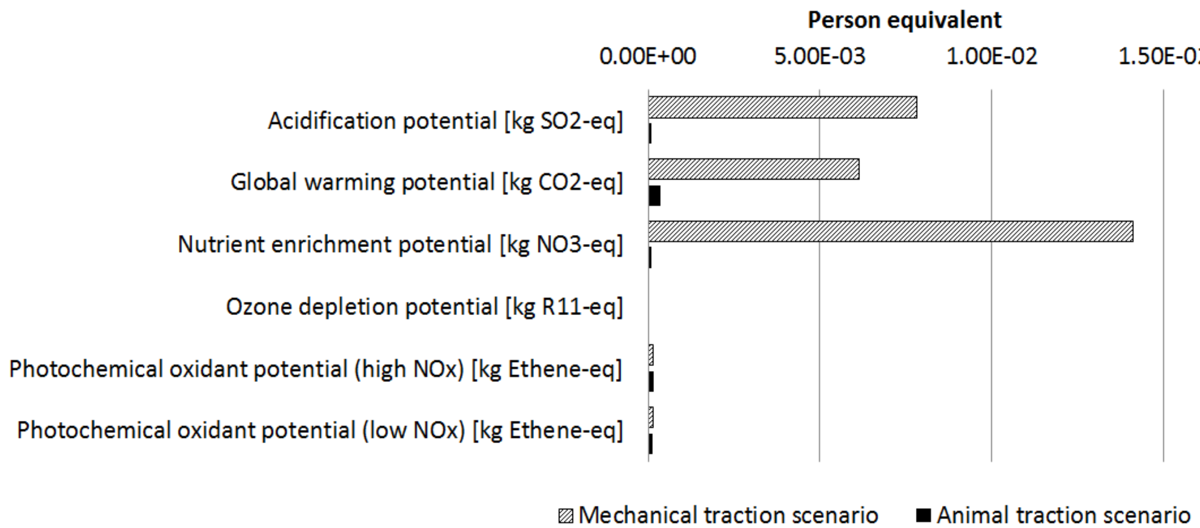

Figure 7. Case B: horticultural task, normalized impact potentials

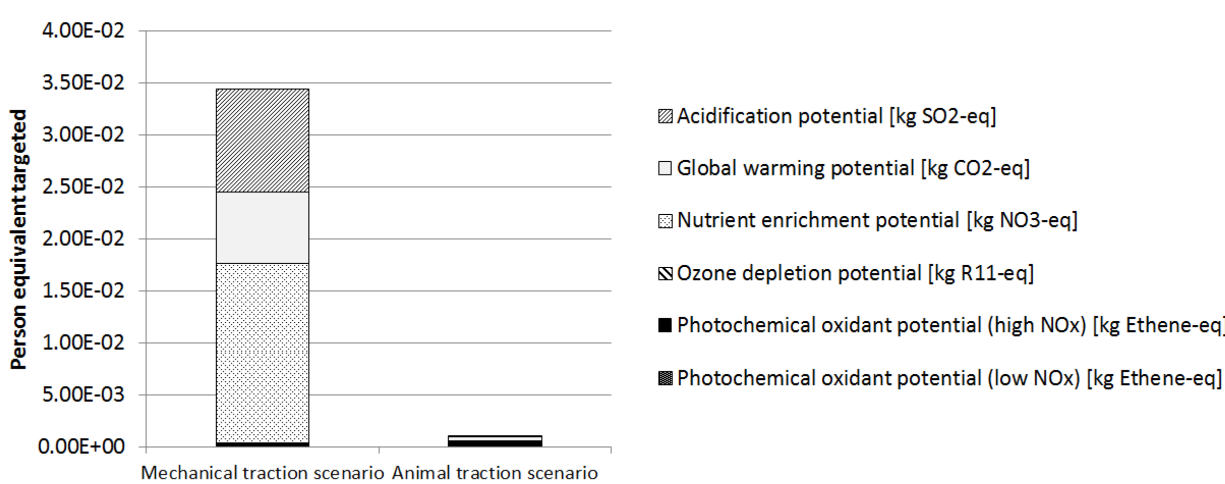

Figure 8. Case B: horticultural task, weighted impact potentials

TABLES

Table 1. Technical characteristics of the animal and the tools for the scenario 'mule forestry tasks'

	Unit	Chainsaw	Billhook	Mule
Useful life	year	8	4	15
Annual use	h	26	30	250
Hourly productivity	kg/h	740	--	528
Power	kW	2.6	--	--
Fuel consumption	kg/h	0.64	--	--
Oil consumption	kg/h	0.5	--	--
Gender		--	--	Female
Age	year	--	--	6
Mass	kg	6	2	280
Height	cm	--	--	149

Table 2. Technical characteristics of the tools for the scenario 'traditional forestry tasks'

		Chainsaw	Winch	Walking	Haul
Useful life	years	8	10	10	30
Annual use	h	44	14	51	42
Hourly productivity	kg/h	1125	804	1200	--
Power	kW	3.4	2.8	10	--
Fuel consumption	kg/h	0.64	0.11	3.35	--
Oil consumption	kg/h	0.5	0.08	--	--
Mass	kg	6	30	110	140

Table 3. Technical characteristics of the animal and the tools for the scenario 'donkey horticultural tasks'

		Donkey	Kassine	Plough	Harrow	Ridge
Useful life	years	15	20	20	20	20
Annual use	h	150	29	2	10	5
Hourly	kg/h	--	--	0.029	0.031	0.023
Gender		Gelding	--	--	--	--
Age	years	10	--	--	--	--
Mass	kg	250	28	2	9	6.5
Height	cm	137	--	--	--	--

Table 4. Technical characteristics of the tools for the scenario 'mechanized horticultural tasks'

		Walking	Plough	Milling	Ridging
Useful life	years	10	--	--	--
Annual use	h	51	--	--	--
Hourly	kg/h	--	0.048	0.064	0.057
Power	kW	10	--	--	--
Fuel consumption	kg/h	--	0.62	0.51	0.57